Journal of Hydrology 556 (2018) 173–181

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

A conceptual framework towards more holistic freshwater conservation planning through incorporation of stream connectivity and thermal vulnerability

P.A. Ramulifho [a,*], N.A. Rivers-Moore [b], H.F. Dallas [c,d], S.H. Foord [a]

[a] Chair in Biodiversity Value and Change in the Vhembe Biosphere Reserve, University of Venda, Private Bag x5050, Thohoyandou 0950, South Africa
[b] Centre for Water Resources Research, University of KwaZulu-Natal, Private Bag x01, Scottsville 3209, South Africa
[c] Freshwater Research Centre, P.O. Box 43966, Scarborough 7975, South Africa
[d] Nelson Mandela Metropolitan University, P.O. Box 77000, Port Elizabeth 6031, South Africa

ARTICLE INFO

Article history:
Received 27 February 2017
Received in revised form 26 October 2017
Accepted 3 November 2017
Available online 7 November 2017
This manuscript was handled by G. Syme, Editor-in-Chief, with the assistance of Helge Bormann, Associate Editor

Keywords:
Adaptive management
Aquatic macroinvertebrate
Catchment conservation
Longitudinal connectivity
Thermophily
Water temperature

ABSTRACT

The thermal regime of rivers plays an important role in the overall health and composition of aquatic ecosystems, and together with flow, is recognised as one of the most influential abiotic drivers of aquatic ecosystem processes affecting species distribution. Changes in thermal conditions in aquatic systems are driven by on-going human-induced climate change, hydrological, regional and structural factors. Here, we quantified the impact of instream impoundments on the natural longitudinal connectivity and estimated thermal vulnerability of catchments based on the functional relationship between changing temperature and the profile gradient of rivers in the eastern portion of South Africa. We identified catchments that are most vulnerable to thermal stress based on cold-water adapted species' tolerance to thermal changes. More than half of all studied catchments include rivers that are relatively intact longitudinally, with notable exceptions being rivers in the central portion of the study area. Thermal condition of high elevation sites is more heavily impacted by impoundments and consequently thermal vulnerability of these sites are higher. Blephariceridae and Notonemouridae, the most thermophobic families, are likely to become locally threatened or extinct, in the absence of connectivity. The quantification of stream connectivity and vulnerability of organisms to thermal changes in river systems are important decision making tools for effective adaptive and holistic conservation planning strategies.

1. Introduction

Climate change is likely to push many aquatic systems past critical temperature thresholds, resulting in severe habitat and ecological degradation requiring bold management interventions and conservation across the globe (Khamis et al., 2014a,b). The thermal regime of rivers plays an important role in the overall health and composition of aquatic ecosystems and is recognised as one of the most influential abiotic drivers of aquatic ecosystem processes (Dallas and Rivers-Moore, 2012; Li et al., 2013; Sheldon, 2012). Aquatic species' growth, metabolism, food availability, migration and reproduction are all driven by water temperature (Caissie, 2006; Dallas and Ketley, 2011; Dallas and Rivers-Moore, 2012). Stream water temperature is driven by a range of spatio-temporal factors at various scales which may be grouped into hydrological, climatic and structural controls such as aspect, stream depth and slope (Caissie, 2006; Dallas, 2008; Poff and Zimmerman, 2010; Poole and Berman, 2001). These factors may act independently or synergistically, making it difficult to accurately quantify the extent to which each factor contributes to water temperature at a point locality (Grab, 2014). While changes in thermal conditions in aquatic systems are largely attributed to ongoing human-induced climate change (climatic drivers), the effect of instream impoundments (hydrological drivers) such as large dams and weirs is often ignored (Bunn and Arthington, 2002; Bush et al., 2012; Filipe et al., 2012; Lawler, 2009). Modification of rivers by impoundment affects one or more spatial and temporal dimensions of a river (Casado et al., 2013; Richter et al., 1997). For example, flow alteration of the magnitude, frequency and timing of natural flow events, and other associated temporal regimes of dam-released water in impounded systems induce thermal changes and pose a considerable threat to aquatic biodiversity (Bunn and Arthington, 2002; Caissie, 2006; Dallas and Ketley,

* Corresponding author.
E-mail address: pfananani.ramulifho@gmail.com (P.A. Ramulifho).

https://doi.org/10.1016/j.jhydrol.2017.11.005
0022-1694/

2011; Li et al., 2013; Poff and Zimmerman, 2010; Richter et al., 1997). Longitudinal barriers disrupt temporal cues (temperature and flow signatures) that in turn differentially affect distribution ranges and breeding success of aquatic organisms (Freeman et al., 2007; Sola et al., 2011). This exerts pressure on aquatic populations and regulates the distribution, abundance and diversity of biota in rivers (Bunn and Arthington, 2002; Poff and Zimmerman, 2010).

Aquatic invertebrates are commonly used as indicators of aquatic ecosystem change because of their variable and specialized range of tolerances and preferences for biotopes (Khamis et al., 2014a; Siddig et al., 2016). Effects of thermal change in aquatic ecosystems on aquatic invertebrate species include changes in the reproductive success and fitness, distribution and range shifts of species, phenology, and physiology, (Dallas, 2008; Dallas and Ross-Gillespie, 2015; Dallas and Rivers-Moore, 2014; Filipe et al., 2012; Lawler, 2009; Walther, 2010). Phenological changes of species include altered development time, voltinism, emergence and mating patterns (Dallas and Ketley, 2011; Dallas and Ross-Gillespie, 2015; Durance and Ormerod, 2007; Walther, 2010). Although every species is not equally responsive to thermal change, physiological changes include changes in growth rate, respiration and secondary productivity (Dallas and Ross-Gillespie, 2015; Olden and Naiman, 2010; Rieman and Isaak, 2010). Thermally-induced species range shifts and community structure changes are associated with changing elevational gradients and increasing water temperature putting a major strain on stenothermic organisms which only survive at relatively low temperatures (for example, Bush et al., 2012; Chessman, 2012; Filipe et al., 2012; Walther, 2010).

The effects of climate change on aquatic biota are determined by their vulnerability, dispersal ability and resilience (Gitay et al., 2011). In this paper, vulnerability is defined as the degree to which a system is susceptible to, and ability to cope with, climate perturbations and other pressures (e.g. anthropomorphic) (De Lange et al., 2010; Gitay et al., 2011). Hydrological connectivity is defined as the ease at which the movement of mass, momentum, energy or organisms is facilitated by longitudinal flow in streams (Freeman et al., 2007). Connectivity enables organisms to migrate from warmer river reaches to cooler reaches at higher elevations (Sheldon, 2012) and other kinds of thermal refugia such as groundwater upwelling zones or cooler tributaries (Dugdale et al., 2013). Resilience in this study is the ability of a system to recover from perturbations (De Lange et al., 2010; Holling, 1973; Rieman and Isaak, 2010). Consideration of connectivity and resilience, and knowledge of species traits such as thermal tolerance (e.g. thermophily), habitat specialization (e.g. rheophily) and dispersal ability, makes it possible to predict species response to thermal change and improve strategies for addressing thermal change in freshwater resources management (Chessman, 2012). Universally, the vast majority of the proposed strategies for managing freshwater resources in a changing climate can be grouped into three types of strategies: those promoting resistance (system ability to remain unchanged in the face of external forces), resilience (ability of a system to recover from perturbations), and change of a system from one state to another (Holling, 1973; De Lange et al., 2010). The conventional strategies for promoting resistance, resilience, and change of freshwater resources are those increasing connectivity of rivers, using indicator species as the primary diagnostic and monitoring tool, removing threats and reducing stresses, expanding reserve networks and measuring irreplaceability of resources (Chessman, 2012; Linke et al., 2007; Rivers-Moore et al., 2011; Siddig et al., 2016). Whereas many freshwater conservation strategies operate within a knowledge deficient environment, a strong need exists to explicitly address these broader environmental variables more holistically, with a stronger emphasis on longitudinal connectivity of streams and thermal vulnerability of aquatic organisms (Hermoso et al., 2011). Conventional strategies for addressing freshwater resources management are far from new; however most effective catchment conservation planning strategy should be holistic in nature including areas of major priority such as anthropogenic factors and environmental gradients driving beta diversity of aquatic species (Jewitt et al., 2016; Poff and Zimmerman, 2010).

Here, we evaluate the potential impacts of instream impoundments and rates of change in river gradient on broad-scale water temperature changes in the province of KwaZulu-Natal (KZN), South Africa. This riverscape was chosen because of its high proportion in levels of water yield, aquatic species richness and endemism in South Africa (Rivers-Moore et al., 2007). It therefore provides a useful template to draw inferences on vulnerability and resilience of selected aquatic macroinvertebrate families because of topographically and climatically diverse landscape and well-studied longitudinal river disconnectivity (Rivers-Moore et al., 2007, 2016). These assessments will provide a holistic screening process for further refining priority catchments already identified in freshwater conservation plans. Our aims in this study were to (1) quantify the impact of instream impoundments on natural longitudinal connectivity; (2) identify the catchments most vulnerable to water temperature changes; and (3) highlight aquatic macroinvertebrate families that are likely to be vulnerable to changes in water temperature.

2. Material and methods

2.1. Study area

Rivers in the province of KwaZulu-Natal in the eastern portion of South Africa were selected for this study. The province covers an area of some 92,000 km^2, between 26°50′ and 31°10′ south of the equator and between 28°50′ and 32°50′ east of the prime meridian line (Eeley et al., 1999). The rivers of KZN flow through a climatically and topographically diverse landscape. These rivers provide habitat for many aquatic associated macroinvertebrates, amphibians, reptiles, and fish species, including at least 26 endemic species, some of which are endangered and critically endangered (Rivers-Moore et al., 2007, 2011). KZN has the second highest number of flagship rivers in South Africa prioritised for the retention of their natural and undisturbed status (Driver et al., 2011). Mean annual precipitation ranges from around 2000 mm to as low as 550 mm in the drier and lower-lying valley regions (Lynch, 2004). While mean air temperature in winter can be as low as 0.4 °C in high-lying areas, it varies considerably towards the in dry lower lying areas of KZN (Grab and Simpson, 2000; Schulze et al., 2005). Mean air temperature during the mid-summer months for the entire province is 28 °C (Eeley et al., 1999). For this assessment, 2nd order streams (Strahler, 1952) were selected, as large impoundments are unlikely to occur in first-order streams (Fig. 1).

2.2. Applicable datasets

Measurements of the connectivity index and vulnerability of rivers to thermal change was based on spatial data layers of instream dams, weirs and waterfalls (Fig. 1). To account for mapping inaccuracies between 1:500,000 rivers and impoundments at a 1:50,000 scale, a 50 m buffer was defined around each impoundment, such that if the buffer intersected a river line, then an instream barrier was assigned. Un-impounded (free-flowing) rivers were verified through using Google Earth. We also acknowledge that natural waterfalls have positive impacts on rivers as they

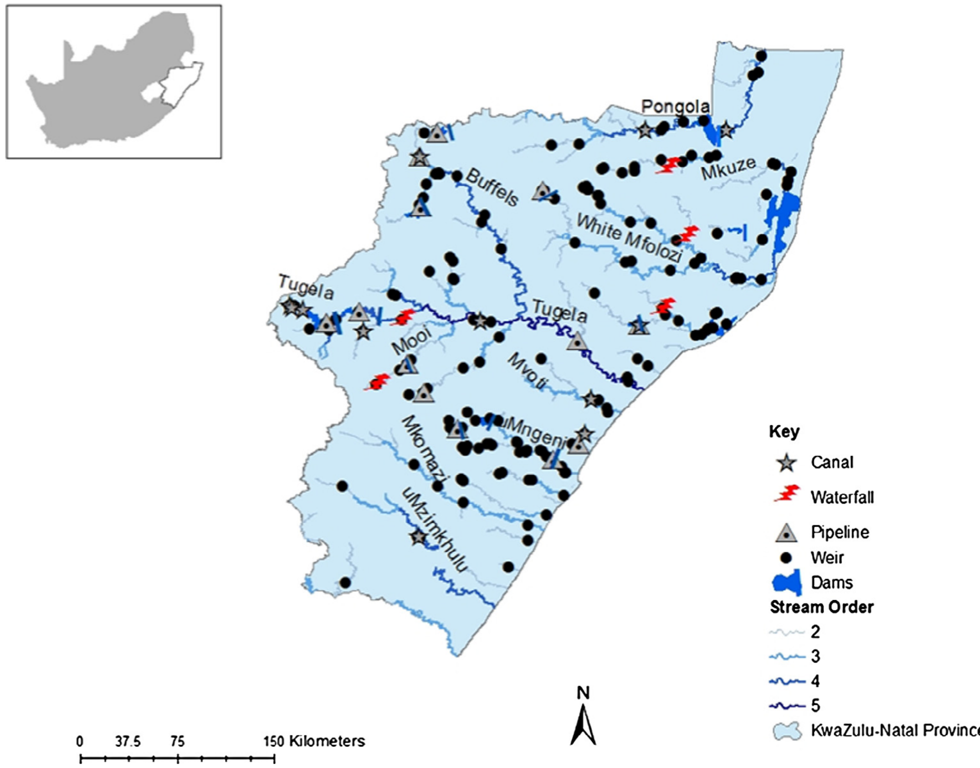

Fig. 1. Map showing study rivers and instream impoundments in the province of KZN South Africa.

can act as barriers to upstream migration of alien species (Karssing et al., 2012). Nevertheless, waterfalls were considered barriers as they equally impede the mobility of native species. Quaternary catchments, were used for the calculation of connectivity and vulnerability. Quaternary catchments defines areas with uniform hydrological characteristics and the primary water planning units in South Africa (Driver et al., 2011). The spatial scale of rivers used was 1:500,000 and this layer included attributes such as stream order, ecoregion type and status, geographic zone, flow variability and stream length (Driver et al., 2011; DWA, 2005). Instream dams, weirs and waterfalls were used to assess the impact of impoundments on longitudinal connectivity and thermal regimes of a stream (Caissie, 2006; DLA-CDSM, 2005; Poff and Zimmerman, 2010). Family level distribution data for aquatic macroinvertebrates were extracted from the River Health Programme (RHP) database (Dallas et al., 2007). The RHP dataset for KZN included 23 natural undisturbed sites out of the 1041 monitoring sites across varying substrate components (rocks, boulders, cobbles, gravel, sand, fine sediment and woody debris snags) and elevation collected over 10 years.

2.3. Impact of impoundments on longitudinal connectivity

The degree of impact of instream impoundments on flow was quantified using the total cumulative score of these obstacles to a rivers' longitudinal connectivity at a quaternary catchment scale (Rivers-Moore et al., 2016). The impact score rating for instream impoundments are adopted from the Australian instream impoundment weight scoring index because of the similarities in flow patterns between Australian and South African rivers (Chiew et al., 1995; Stein et al., 2002). Cumulative impact scores for instream impoundments were assigned on a 0–1 scale: as 1.0, 0.6, 0.3 and 0.1 for dams, canals, weirs and waterfalls respectively. The Longitudinal Connectivity Index (LCI) was calculated as a product of the total impact score per quaternary catchment divided by the maximum score of the overall observed impact (Eq. (1)) (Rivers-Moore et al., 2016). The LCI uses the highest impact score (Max.score) observed for a catchment as a benchmark for a worst case scenario longitudinal disturbance to standardize all other catchment scores to range between 0 and 1. Catchments with a score value of 0 are well connected, while catchments with a score of 1 were highly disconnected longitudinally. Results were presented on the basis of natural breakpoints between score classes.

$$\text{Longitudinal Connectivity Index (LCI)} = \frac{\sum_{i=1}^{n} Barrier\ weights}{Max.score} \quad (1)$$

2.4. Assessing thermal vulnerability of upstream reaches

The most pragmatic approach of relating the LCI to conservation planning goal is to identify zones that are thermally vulnerable to climate change effects. This was done using the rate of thermal change in response to changes in stream gradient. We studied downstream to upstream thermal vulnerability by quantifying temperature changes along an elevational gradient in the uMzimkhulu River (Fig. 1). Mean annual water temperature was measured at three elevations; 6, 977, and 1430 m a.s.l., respectively approximately 9, 109, and 137 km upstream of a river's mouth.

Thermal vulnerability was then used as a base layer in assessing thermal resilience of catchments in 13 streams with varying elevational gradients in KZN. Rates of elevation change in river profiles were used as a surrogate for vulnerability, based on the fact that temperature changes are more rapid with steeper gradients. The gradient of a stream was measured as the highest point minus lowest point divided by the longest distance minus the shortest distance of the river. Streams with an elevation gradient greater than the average elevation gradient for the 13 streams selected, were considered to have high vulnerability to thermal change (Heino et al., 2009; Sheldon, 2012; Rieman and Isaak, 2010). Thermal Resilience was measured as the product of thermal

vulnerability and LCI (Eq. (2)), such that a well-connected river with a low elevation gradient is less thermally vulnerable and would have high thermal resilience. We also distinguished between moderate and low thermal resilience. Streams with low thermal resilience are very disconnected and highly vulnerable thermally, while moderate thermal resilient streams could be well connected but with high thermal vulnerability or highly disconnected but less thermally vulnerable (Fig. 2).

$$\text{Thermal Resilience} = \textit{Thermal Vulnerability} * \textit{LCI} \quad (2)$$

2.5. Thermal vulnerability of cold-adapted families and catchment conservation priorities

To estimate the vulnerability (or risk where resilience is low) of cold-water families, this study used thermophily (degree of preference for high or low temperature) for a subset of macroinvertebrates families occurring in KZN rivers. The estimate of thermophily of aquatic macroinvertebrate families was undertaken for seven families (Notonomouridae (Plecoptera), Philopotomidae (Trichoptera), Paramelitidae (Amphipoda), Blephariceridae (Diptera), Simuliidae (Diptera), Heptageniidae (Ephemeroptera) and Gyrinidae (Coleoptera)), including six ranked as thermally sensitive [Thermal Sensitivity Rank (TSR) = 1] and one as thermally tolerant (TSR = 3). Macroinvertebrate families used include Thermophily is a product of the mean instantaneous temperature (ITmean) associated with samples in which that family was detected, divided by mean water temperature (WTmean) of all samples (Chessman, 2012) (Eq. (3)). TSR values were derived from experimentally generated Critical Thermal Maxima values (Dallas and Rivers-Moore, 2012). Spot water temperature data at sites where these families were present in KZN Rivers were extracted from the RHP database (Dallas et al., 2007). The mean water temperature of 17.95 °C was generated from all nationwide sites (5302) where aquatic macroinvertebrate samples were collected during the RHP. Families with lower estimates of thermophily were considered "thermophobic", while families with greater estimates were "thermorphilic" (Dallas et al., 2007). Thermophily was calculated as the ratio of thermophilic (warm-adapted) to thermophobic (cold-adapted) organisms, and this was compared between sites.

$$\text{Thermophily} = \frac{\textit{ITmean}}{\textit{WTmean}} \quad (3)$$

Catchment Conservation Priority (CCP) is the sum of the availability of Thermophobic taxa and Thermal Resilience in catchments (Eq. (4)). Systems with high CCP, indicative of the presence of thermophobic family in catchments with low to moderate Thermal Resilience, are earmarked as hotspots for freshwater conservation planning.

$$\text{Catchment Conservation Priority} = \textit{Thermophobic Taxa} + \textit{Thermal Resilience} \quad (4)$$

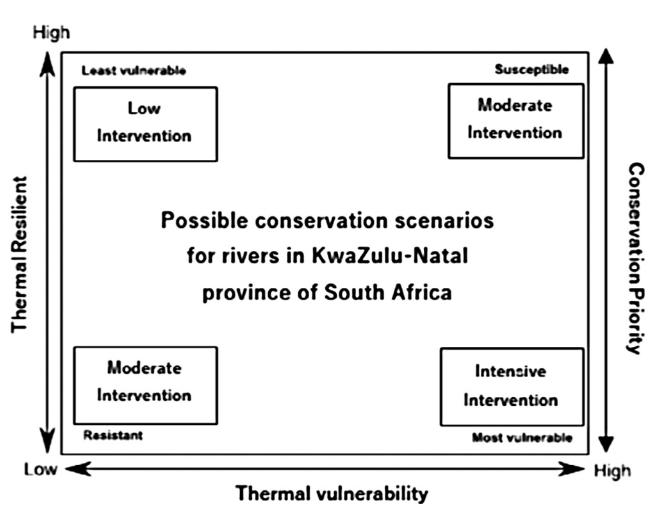

Fig. 2. Possible scenarios for conservation planning of rivers in KwaZulu-Natal province (adopted from Khamis et al. (2014b)).

3. Results

3.1. Impact of impoundments on longitudinal connectivity

A total of 275 instream barriers were recorded along 7900 km of rivers of stream order class ≥2 at a mapping scale of 1:500 000, extending over 214 quaternary catchments. Our assessments showed that longitudinal connectivity generally decreased with increasing stream order. Only 27% of total river length (with average length of 45 km) had undisturbed free-flowing conditions with most of them being small tributaries (Figs. 1 and 3). More than half (66.37%) of all quaternary catchments contained rivers with low LCI (well connected) impact scores of between 0.00 and 0.05 (Fig. 4). Most of the natural catchments were found in the southernmost and central regions of KZN. The highest disturbance class contained 2.3% of all catchments and include the lower and middle sections of the uMngeni and Tugela River. The entire length of the uMngeni River has a total of four clustered large dams and also other instream impoundment factors (weirs and waterfalls) contributing to an unstandardized cumulative disconnectivity impact score of 7.5.

3.2. Resilience of catchments to thermal change

The mean profile gradient of the 13 high elevation streams that were used to assess the thermal vulnerability and resilience of streams was 5.29 (which represents the thermal vulnerability threshold), i.e. streams with an elevation gradient less than the overall mean elevation gradient were considered less vulnerable to thermal changes. Six streams that are least vulnerable to increasing temperatures are found in the lowlands of the central and northern parts of KZN (Table 1). Of the 13 streams, one had the lowest profile gradient of 2.02 and was therefore the least thermally vulnerable stream. Seven streams had elevation gradients exceeding the 5.29 mean profile gradient, amongst them, the Mdloti River was the most vulnerable to thermal change in the KZN province with an elevation gradient of 11.05 (Table 1). All seven of these thermally vulnerable streams are found in the southern parts of KZN which consist mostly of a diverse range of landscapes. Regarding resilience, two streams had the lowest thermal resilience. These two streams descend from the Drakensberg highland areas and have both recorded a high LCI score. Impounding of these two streams further reduces the downstream–upstream routes of organisms and poses a great threat to cold-water specialized families. More than half of assessed streams (8 of 13) had moderate resilience to thermal change. These streams either exhibited high LCI scores or a high vulnerability status to thermal change due to a high elevational gradient. The remaining three streams are highly resilient with 'low LCI' scores and low thermal vulnerability.

3.3. Vulnerability of cold-water adapted families and catchment conservation priorities

Thermophily of macroinvertebrate families assessed varied between 0.79 and 1.00 (Table 2). The most thermophobic taxa included Blephariceridae and Notonemouridae with a mean

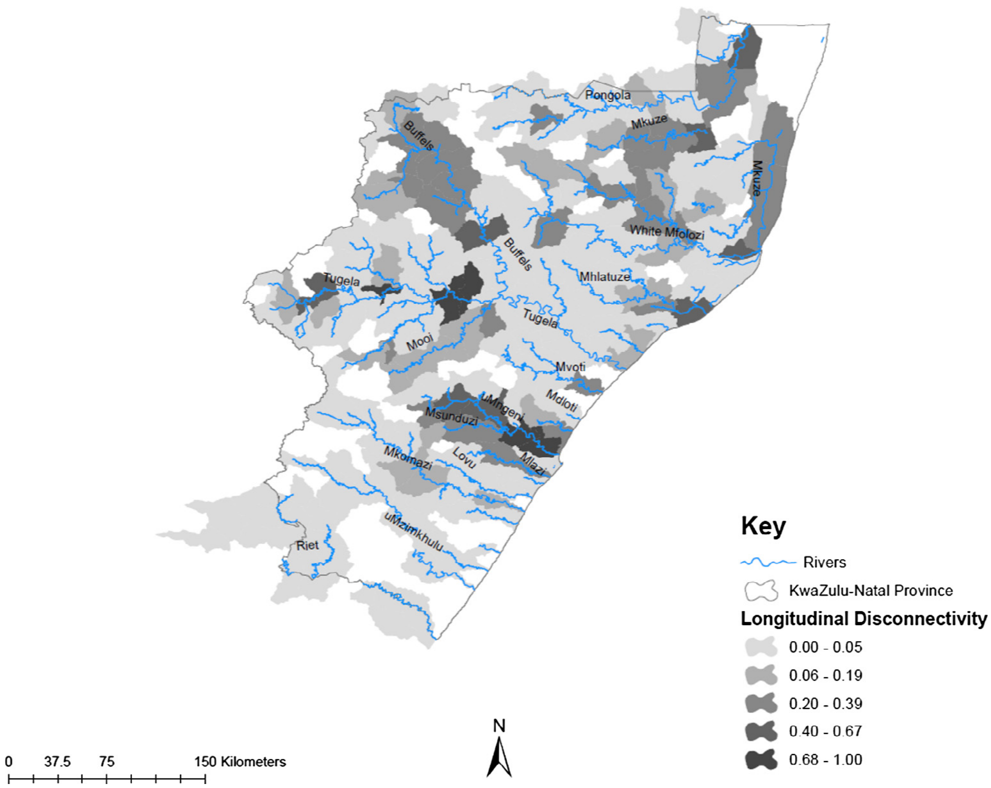

Fig. 3. Standardized provincial longitudinal disconnectivity index based on cumulative scores of weighted in-stream impoundments at quaternary catchment level.

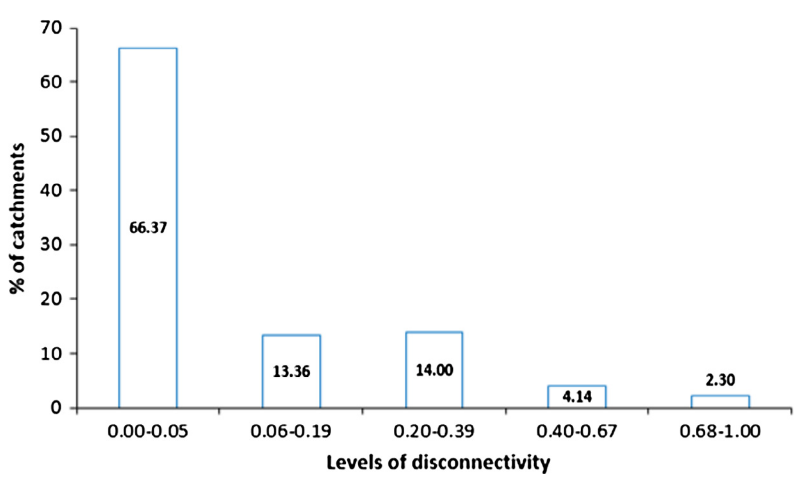

Fig. 4. Percentage of catchments at different levels of longitudinal disconnectivity of rivers.

instantaneous temperature of 14.3 °C and 14.8 °C, and estimate of thermophily of 0.79 and 0.82 respectively. Gyrinidae, Simuliidae and Heptageniidae were the most thermophilic family with estimate of thermophily at 1.00, 0.97 and 0.96 respectively. Two catchment areas were identified as having high conservation priority, viz. the headwater reaches of both the Mkomazi and uMngeni Rivers (Table 1). Both these catchments have records for at least one thermophobic family (Fig. 5).

4. Discussion

The existing baseline freshwater conservation plan for the KZN region identifies priority areas based on the irreplaceability of freshwater biodiversity and vulnerability of surface water yield zones to anticipated land use threats within the province (Rivers-Moore et al., 2011). Rivers-Moore et al. (2016) proposed the use of a connectivity index layer to complement these criteria in setting priorities for conservation and rehabilitation of KZN rivers. The current study extends the utility value of the LCI by including both thermal vulnerability and the proportion of thermophobic taxa to refine selection criteria. Based on these criteria, two rivers (uMngeni and Mkomazi) had high conservation priority. Both had high thermal vulnerabilities and hosted thermophobic taxa. The uMngeni also falls within the 2.3% of all catchments that recorded the highest disconnectivity score (LCI). Disconnected catchments are a great threat to potential compensatory migration of thermal affected taxa to higher elevations or any other refuge (Chessman, 2012). The incorporation of the thermal vulnerability assessment

Table 1
Thermal vulnerability, thermal resilience and conservation priority of KZN Rivers based on gradient, connectivity and ratio of thermophilic to thermophobic families.

River	Change in gradient	Thermal vulnerability based on mean gradient point (5.29)	Longitudinal disconnectivity score	Thermal resilience (low, moderate and high)	Family thermophily ratio (thermophilic: thermophobic)	Conservation priority
Mkomazi	7.20	High	0.07	Moderate	4:1	High
uMngeni	6.04	High	1.22	Low	2:1	High
Mlazi	5.76	High	0.15	Moderate	3:0	Low
uMzimkulu	6.54	High	0.00	Moderate	3:0	Low
White Mfolozi	3.32	Low	1.07	Moderate	1:0	Low
Mooi	2.21	Low	0.04	High	1:0	Low
Pongolo	2.02	Low	0.06	High	1:0	Low
Tugela	3.12	Low	0.23	High	1:0	Low
Buffels	3.23	Low	1.58	Moderate	1:0	Low
Lovu	6.96	Low	0.43	Moderate	Not assessed	Low
Mdloti	11.05	High	0.03	Moderate	Not assessed	Low
Mhlatuze	4.91	Low	0.79	Moderate	Not assessed	Low
Msunduzi	7.79	High	1.00	Low	Not assessed	Low

Table 2
Estimates of thermophily for aquatic macroinvertebrate families.

Families	Number of Sites	Mean Instantaneous Temperature (°C)	Mean Water Temperature (°C)	Estimate of Thermophily
Blephariceridae	110	14.3	18	0.79
Notonemouridae	395	14.8	18	0.82
Amphipoda	167	16.4	18	0.91
Philopotamidae	634	16.8	18	0.93
Heptageniidae	1295	17.3	18	0.96
Simuliidae	3596	17.5	18	0.97
Gyrinidae	2497	17.9	18	1.00

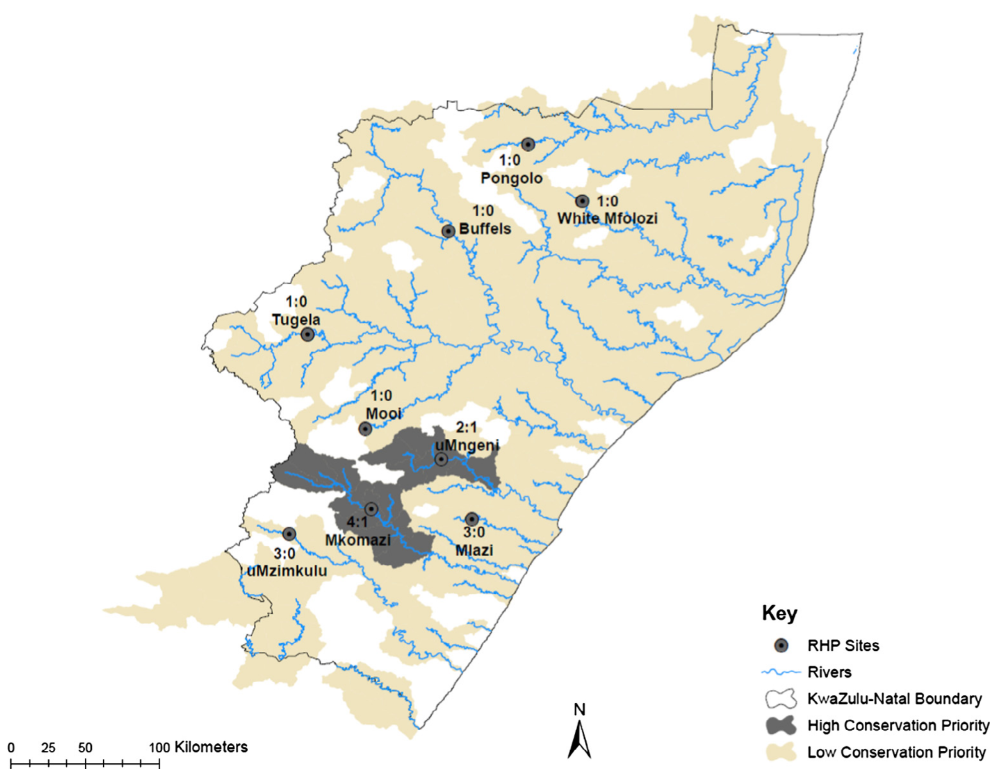

Fig. 5. The distribution of studied RHP sites and catchment that have high and low conservation priority based on level of thermal vulnerability and occurrence of thermophobic taxa.

of sensitive taxa to the existing conservation plans is a useful technique to identify priorities at finer scales.

Modern day frameworks for prioritizing conservation hotspots are based on two critical areas of concern, viz. landscape conservation capacity and vulnerability to climate change (Khamis et al., 2014b) with little consideration of dimensions of stream connectivity and taxonomic response. Extending the current conservation initiatives to include all three criteria (disconnectivity, thermal

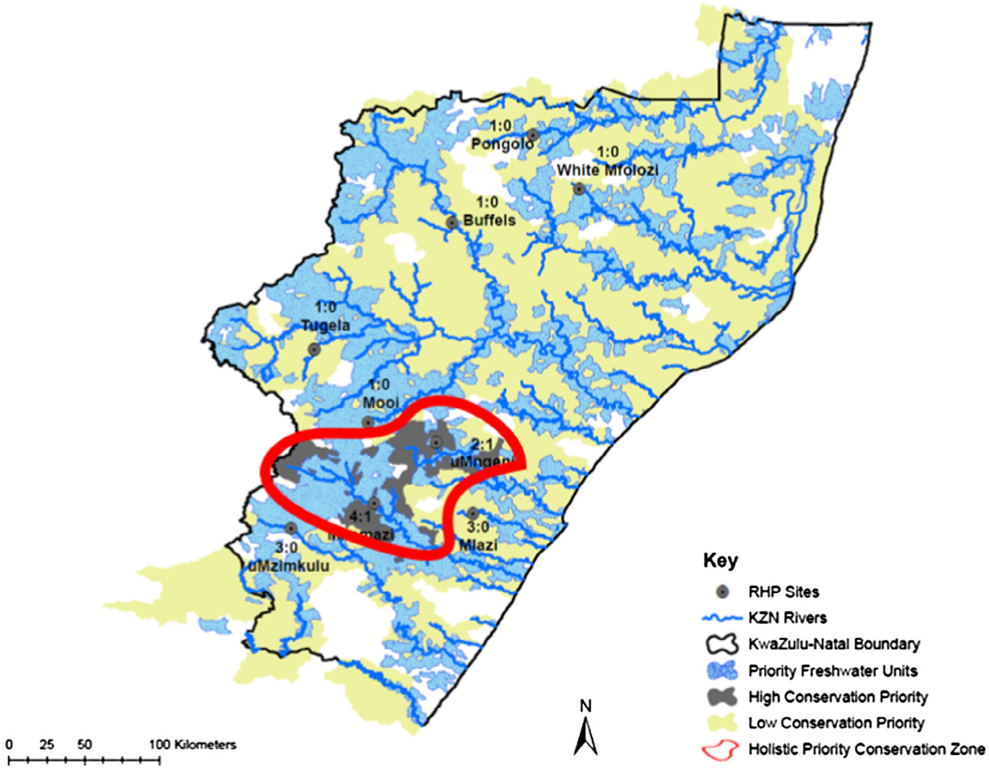

Fig. 6. Holistic priority conservation zone based on thermal vulnerable taxa and combined connectivity score linked to priority freshwater planning units for KwaZulu-Natal of Rivers-Moore et al. (2011).

vulnerability and thermophoby) would allow for priorities to address specific threats (Wilson et al., 2007). Also, the process of monitoring and maintaining the river's ability to adapt to change, using iterative adaptive management principles, is an ideal approach for dealing with the uncertainties surrounding future climatic conditions and future climate impacts (Rivers-Moore et al., 2007; Pace et al., 2013). Here we embed the areas of high conservation priority as indicated by the inclusive assessment of this study to the existing priority areas for freshwater planning which based on their conservation importance for KZN (Fig. 6), as assessed and identified by Rivers-Moore et al. (2011). In the most affected river (the uMngeni) of this study in terms of its high thermal vulnerability, low thermal resistance and low longitudinal connectivity score falls within the priority planning areas of Rivers-Moore et al. (2011), and this shows the extent to which the holistic approach of this study can identify finer scale priority areas. We believe that adding the aspects of thermal vulnerability of rivers, longitudinal connectivity and sensitive taxa to the existing conservation planning assessments contribute towards an improved management and decision marking tool (Fig. 6).

However, a major challenge for this technique is an inadequacy of long-term data for freshwater invertebrates at finer spatial and taxonomic scales. Taxonomic data will enable setting quantitative conservation targets which in turn provide a base for an assessment of the conservation value of an area (Rivers-Moore et al., 2011). It is also worth noting that connectivity of rivers goes beyond just a single longitudinal dimension to cover a range of lateral, vertical and temporal dimensions, enabling full consideration of ecological processes (Freeman et al., 2007). The approach presented here requires minimal consideration of dispersal abilities, life history and habitat requirements of taxa concerned and strengthens conservation planning at the level of decision making by identifying tipping points in the aquatic systems.

The use of macroinvertebrate families in modeling thermal vulnerability and thermal resilience acknowledge water temperature and stream flow (longitudinal connectivity) as a primary driver of distribution. Indicator species are ideal for conservation planning as they accurately scale evident information surrounding present climatic changes in streams and other freshwater systems (Lawler, 2009). Increasing water temperature is likely to reduce both the habitat range and population size of thermophobic taxa, including Blephariceridae and Notonemouridae, in high elevation streams, such as the Mkomazi and uMngeni in this study. Rising air temperature and warming of streams will narrow the habitat range for cold-adapted species along elevated gradients (Heino et al., 2009; Lawler, 2009). Chessman (2009) also found that at a global scale, long-term survival of strength of thermophobic families is likely to decline due to worsening thermal conditions at upper catchments. Connectivity, a key element of this approach in the conservation framework of this current study, is obligatory when macroinvertebrate respond to catastrophic effects of thermal change (Rivers-Moore et al., 2016). Heino et al. (2009) has shown that the ease at which many species expand their ranges to favorable environments depends on the level connectivity in river systems. Maintaining or achieving the most desirable LCI is a challenge in conservation planning. This study found that greater proportion of all assessed catchments in KZN had streams that are disturbed by one or more impoundment types. In the absence of connectivity, cold-water species are likely to become locally extinct, eventually leading to a loss of genetic diversity (Buisson et al., 2008; Bush et al., 2012; Durance and Ormerod, 2007).

5. Conclusion

- The catchment-based approach illustrated in this study suggest that conventional catchment conservation planning based on biodiversity priority and irreplaceability is necessary but not sufficient for effective management and conservation planning of freshwater resources.

- The framework outlined in this study enabled successful identification of areas where conservation should be prioritized based on elements of a longitudinal connectivity index, stream elevation (thermal vulnerability) and thermal sensitivity of macroinvertebrate species.
- The use of fine scale taxonomic and spatial data, and consideration of all dimensions of stream connectivity is recommended for effective conservation strategies and planning particularly in most thermal vulnerable sections of the catchments.
- Analyses of thermal vulnerability of streams should include projections of how and where temperature will change, this is crucial for adaptive strategies in freshwater conservation.
- Management strategies can also focus on prioritization of those catchments that are thermally vulnerable but are relatively connected and rehabilitate those that are vulnerable but disconnected.
- The holistic approach presented in this paper has the potential to assist in highlighting river systems with higher resilience as preferential systems for expanding protected area networks.

Acknowledgements

This work was supported by the Water Research Commission of South Africa (Project K5/2182). NRF-DST South African Research Chair in Biodiversity Value and Change is acknowledged for providing an office space during the writing of this manuscript. The comments of two anonymous reviewers of this manuscript are also much appreciated.

References

Buisson, L.A., Thuiller, W.Z., Lek, S., Lim, P., Grenouillet, G., 2008. Climate change hastens the turnover of stream fish assemblages. Glob. Change Biol. 14, 2232–2248.
Bunn, S.E., Arthington, H., 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environ. Manage. 30 (4), 492–507.
Bush, A., Nipperess, D., Turak, E., Hughes, L., 2012. Determining vulnerability of stream communities to climate change at the landscape scale. Freshw. Biol. 57, 1689–1701.
Caissie, D., 2006. The thermal regime of rivers: a review. Freshw. Biol. 51, 1389–1406.
Casado, A., Hannah, D.M., Peiry, J.L., Campo, A.M., 2013. Influence of dam-induced hydrological regulation on summer water temperature: Sauce Grande River, Argentina. Ecohydrology 6 (4), 523–535.
Chessman, B.C., 2009. Climatic changes and 13-year trends in stream macroinvertebrate assemblages in New South Wales, Australia. Glob. Change Biol. 15, 2791–2802.
Chessman, B.C., 2012. Biological traits predict shifts in geographical ranges of freshwater invertebrates during climatic warming and drying. J. Biogeogr. 39, 957–969.
Chiew, F.H.S., McMahon, T.A., Peel, M.C., 1995. Some Issues of Relevance to South African Streamflow Hydrology. Seventh South African Hydrology Symposium. Rhodes University, Grahamstown.
Dallas, H.F., 2008. Water temperature and riverine ecosystems: an overview of knowledge and approaches for assessing biotic response, with special reference to South Africa. Water SA 34, 393–404.
Dallas, H.F., Molteno, A., Ewart-Smith, J., Janssens, P., 2007. Rivers Database Version 3: User Manual. Report for the Department of Water Affairs and Forestry River Health Programme. Prepared by The Freshwater Consulting Group in association with Soft Craft Systems. 71pp.
Dallas, H.F., Ketley, Z.A., 2011. Upper thermal limits of aquatic macroinvertebrates: comparing critical thermal maxima with 96-LT50 values. J. Therm. Biol. 36, 322–327.
Dallas, H.F., Rivers-Moore, N.A., 2012. Critical Thermal Maxima of aquatic macroinvertebrates: towards identifying bioindicators of thermal alteration. Hydrobiologia 679, 61–76.
Dallas, H.F., Rivers-Moore, N.A., 2014. Ecological consequences of global climate change for freshwater ecosystems in South Africa. South Afr. J. Sci., 110. http://dx.doi.org/10.1590.
Dallas, H.F., Ross-Gillespie, V., 2015. Sublethal effects of temperature on freshwater organisms, with special reference to aquatic insects. Water SA 41 (5), 712–726.
De Lange, H.J., Sala, S., Vighi, M., Faber, J.H., 2010. Ecological vulnerability in risk assessment: a review and perspectives. Sci. Total Environ. 408, 3871–3879.
Department of Land Affairs: Chief Directorate of Surveys and Mapping (DLA-CDSM), 2005. Waterbodies 1:50,000 Shapefile. Chief Directorate of Surveys and Mapping, Mowbray.
Driver, A., Nel, J.L., Strydom, W.F., Maherry, A., Petersen, C., Hill, L., Nienaber, D.J.S., Deventer, H., Swartz, E., Smith-Adao, L.B., 2011. National Freshwater Ecosystem Priority Areas in South Africa: Atlas of Maps to support sustainable development of water resources. Report No. 1801/2/11.Water Research Commission, Pretoria, South Africa.
Dugdale, S.J., Bergeron, N.E., St-Hilaire, A., 2013. Temporal variability of thermal refuges and water temperature patterns in an Atlantic salmon river. Remote Sens. Environ. 136, 358–373.
Durance, I., Ormerod, S.J., 2007. Climate change effects on upland stream macroinvertebrates over a 25-year period. Glob. Change Biol. 13, 942–957.
Department of Water Affairs (DWA), 2005. River Network 1:500 000. Institute for Water Quality Studies, Department of Water Affairs, Private Bag X313, Pretoria, 0001. http://www.dwaf.gov.za/IWQS/gis_data/river/rivs500k.html (accessed 12.09.13).
Eeley, H.A., Michael, J.L., Steven, E., 1999. The influence of climate change on the distribution of indigenous forest in Kwazulu-Natal, South Africa. J. Biogeogr. 26, 595–617.
Filipe, A., Lawrence, J.E., Bonada, N., 2012. Vulnerability of stream biota to climate change in Mediterranean climate regions: a synthesis of ecological responses and conservation challenges. Hydrobiologia 719, 331–352.
Freeman, M.C., Pringle, C.M., Jackson, R.C., 2007. Hydrological connectivity and the contribution of stream headwater to ecological integrity at regional scale. J. Am. Water Resour. Assoc. 43 (1), 5–14.
Gitay, H., Finlayson, C.M., Davidson, N.C., 2011. A Framework for assessing the vulnerability of wetlands to climate change. Ramsar Technical. Report No. 5/ CBD Technical Series No. 57. Ramsar Convention Secretariat, Gland, Switzerland & Secretariat of the Convention on Biological Diversity, Montreal, Canada.
Grab, S., 2014. Spatio-temporal attributes of water temperature and macroinvertebrate assemblages in the headwaters of the Bushmans River, southern Drakensberg. Water SA 40, 19–26.
Grab, S.W., Simpson, A.J., 2000. Climatic and environmental impacts of cold fronts over KwaZulu- Natal and the adjacent interior of southern Africa. S. Afr. J. Sci. 96, 602–608.
Heino, J., Virkkala, R., Toivonen, H., 2009. Climate change and freshwater biodiversity: detected patterns, future trends and adaptations. Biol. Rev. 84, 39–54.
Hermoso, V., Linke, S., Prenda, J., Possingham, H.P., 2011. Addressing longitudinal connectivity in the systematic conservation planning of fresh waters. Freshw. Biol. 56, 57–70.
Holling, C.S., 1973. Resilience and stability of ecological systems. Annu. Rev. Ecol. Syst. 4, 1–23.
Jewitt, D., Goodman, P.S., O'Connor, T.G., Erasmus, B.F.N., Witkowski, E.T.F., 2016. Mapping landscape beta diversity of plants across KwaZulu-Natal, South Africa, for aiding conservation planning. Biodivers. Conserv. 25, 2641–2654.
Karssing, R.J., Rivers-Moore, N.A., Slater, K., 2012. Influence of waterfalls on patterns of association between trout and Natal cascade frog Hadromophyrnenatalensis tadpoles in two headwater streams in the uKhahlamba Drakensberg Park World Heritage Site, South Africa. Afr. J. Aquatic Sci. 37, 107–112.
Khamis, K., Hannah, D.M., Clarvis, M.H., Brown, L.E., Castella, E., Milner, A.M., 2014a. Alpine aquatic ecosystem conservation policy in a changing climate. Environ. Sci. Policy 43, 39–55. https://doi.org/10.1016/j.envsci.2013.10.004.
Khamis, K., Hannah, D.M., Brown, L.E., Tiberti, R., Milner, A.M., 2014b. The use of invertebrates as indicators of environmental change in alpine rivers and lakes. Sci. Total Environ. 493, 1242–1254.
Lawler, J.J., 2009. Climate change adaptation strategies for resource management and conservation planning. N. Y. Acad. Sci. 1162, 79–98.
Li, F., Chung, N., Park, Y., 2013. Temperature change and macroinvertebrate biodiversity: assessments of organism vulnerability and potential distributions. Clim. Change. https://doi.org/10.1007/s10584-013-0720-9.
Linke, S., Pressey, R.L., Bailey, R.C., Norris, R.H., 2007. Management options for river conservation planning: condition and conservation re-visited. Freshw. Biol. 52, 918–938.
Lynch, S.D., 2004. Development of a Raster Database of Annual, Monthly and Daily Rainfall for Southern Africa. WRC Report 1156/1/04. Water Research Commission, Pretoria, RSA.
Olden, J.D., Naiman, R.J., 2010. Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity. Freshw. Biol. 55, 86–107.
Pace, G., Bonada, N., Prat, N., 2013. Long-term effects of climatic–hydrological drivers on macroinvertebrate richness and composition in two Mediterranean streams. Freshw. Biol. https://doi.org/10.1111/fwb.12129.
Poff, N.L., Zimmerman, J.K.H., 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshw. Biol. 55, 194–205.
Poole, G.C., Berman, C.H., 2001. An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation. Environ. Manage. 27 (6), 787–802.
Richter, B.D., Baumgartner, J.V., Wigington, R., Braun, D.P., 1997. How much water does a river need? Freshw. Biol. 37, 231–249.
Rieman, B.E., Isaak, D.J., 2010. Climate change, aquatic ecosystems, and fishes in the Rocky Mountain West: implications and alternatives for management. Gen. Tech. Rep. RMRS-GTR-250. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. US.
Rivers-Moore, N.A., Goodman, P.S., Nkosi, M.R., 2007. An assessment of the freshwater natural capital in KwaZulu-Natal for conservation planning. Water SA 33 (5), 655–674.

Rivers-Moore, N.A., Goodman, P.S., Nel, J.L., 2011. Scale-based freshwater conservation planning: towards protecting freshwater biodiversity in KwaZulu-Natal, South Africa. Freshw. Biol. 56, 125–141.
Rivers-Moore, N., Mantel, S., Ramulifho, P., Dallas, H., 2016. A disconnectivity index for improving choices in river protected area management. Aquatic Conserv: Mar. Freshw. Ecosyst. 26 (Suppl. 1), 29–38.
Schulze, R.E., Dlamini, D.J.M., Horan, M.J.C., 2005. The Thukela Catchment: Physical and Socio-Economic Background. In: Schulze, R.E. (Ed.) Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation. WRC Report 1430/1/05. Chapter 10, 191 – 209. Water Research Commission, Pretoria, RSA.
Sheldon, A.L., 2012. Possible climate-induced shift of stoneflies in a southern Appalachian catchment. Freshw. Sci. 31, 765–777.
Siddig, A.A.H., Ellison, A.M., Alison, O., Villar-Leeman, C., Lau, M.K., 2016. How do ecologists select and use indicator species to monitor ecological change? Insights from 14 years of publication in Ecological Indicators. Ecol. Ind. 60, 223–230.
Sola, C., Marc, O., Quim, P., Nuria, S., Aida, Q., Monica, B., Anna, C., Antoni, M., 2011. Longitudinal connectivity in hydromorphological quality assessments of rivers. The ICF index: a river connectivity index and its application to Catalan rivers. Limnetica 30 (2), 273–292.
Stein, J.L., Stein, J.A., Nix, H.A., 2002. Spatial analysis of anthropogenic river disturbance at regional and continental scales: identifying the wild rivers of Australia. Landscape Urban Plann. 60, 1–25.
Strahler, A.N., 1952. Hypsometric (area-altitude) analysis of erosional topography. Geol. Soc. Am. Bull. 63, 1117–1142.
Walther, G.R., 2010. Community and ecosystem responses to recent climate change. Biol. Sci. 365, 2019–2024.
Wilson, K.A., Underwood, E.C., Morrison, S.A., Klausmeyer, K.R., Murdoch, W.W., Reyers, B., Wardell-Johnson, G., Marquet, P.A., Rundel, P.W., McBride, M.F., et al., 2007. Conserving biodiversity efficiently: what to do, where and when. PLoS Biol. 5, 1850–1861.